AN EVAPOTRANSPIRATION RESEARCH FACILITY USING MONOLITHIC LYSIMETERS FROM THREE SOILS

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ABSTRACT. *The evapotranspiration research facility at Bushland, Texas, provides an environment for intensive evapotranspiration and plant water stress research with monolithic lysimeters. Forty-eight monoliths were collected from three major soils in the Southern High Plains so water management treatments, cultural systems, and crop varieties can be replicated. To collect the monoliths, bottomless, rectangular steel boxes were pressed into the soil with hydraulic jacks connected to concrete piers. The monoliths were then tilted into an excavated trench to shear the bottom surface and removed with a crane. The 0.75 m × 1.0 m (30 in. × 40 in.) rectangular area of the monoliths provides normal plant spacing geometry, and the 2.3-m (7.6 ft) deep soil profile with suction drainage allows a normal soil water potential profile to develop. A 13 m × 18 m (42 ft × 60 ft) rain shelter prevents unwanted precipitation on the lysimeters, and soil water levels are controlled with a drip irrigation system. Evapotranspiration is calculated from lysimeter mass changes measured with a load cell suspended from a bridge crane inside the rain shelter.* ***Keywords.*** *Evapotranspiration, Plant water stress, Research, Monolithic lysimeters.*

Intensive soil-plant-water investigations can be conducted efficiently with soil monoliths set in small plot areas and protected by rain shelters. Hiler (1969) and Meyer et al. (1985) describe facilities utilizing soil monoliths and rain shelters for quantifying crop drainage requirements and determining irrigation effects on wheat, respectively. Monoliths in evapotranspiration and plant water stress facilities must represent field conditions and be suitable for experimental designs. The surface area and shape of the monoliths must allow several plants to be grown with normal crop geometry. The depth must be sufficient to provide a "normal" water potential profile (van Bavel, 1961). In addition, a sufficient number of monoliths to replicate treatments such as water management, cultural systems, and crop varieties are desirable. Soil monoliths are usually obtained by pressing bottomless steel boxes or cylinders into the soil and undercutting them at the desired depth.

Rain shelters are used to exclude rainfall from plot areas while other aspects of the environment remain largely unchanged. Precisely controlled quantities of irrigation water can be applied according to an experimental design. With better defined treatment effects, hypotheses can be tested with higher levels of confidence. Foale et al. (1986) reviewed and evaluated rain shelters from five countries, and showed that structural components and control systems for many of the rain shelters were similar.

This article describes an evapotranspiration research facility to meet the needs discussed above. The facility utilizes 48 monolithic lysimeters from three different soils in the Southern High Plains of the United States.

EVAPOTRANSPIRATION RESEARCH FACILITY

The evapotranspiration research facility uses monolithic lysimeters of three benchmark soils grouped together within two lysimeter pits (fig. 1). For precise control of water inputs, the lysimeters and surrounding area are drip irrigated, and the lysimeters can be covered with a rain shelter. Evapotranspiration is calculated from mass changes in the lysimeters measured with a load cell suspended from a bridge crane within the rain shelter. This design utilizes the rain shelter building to support the crane and minimizes wind interference during weighing. The bridge crane is also used to move lysimeters in and out of the pits and to arrange lysimeters for statistical designs.

RAIN SHELTER

The rain shelter is a metal building with all drive components and control sensors mounted on the building (fig. 2). The design was patterned after the one by Ries and Zachmeier (1985) at Mandan, North Dakota. The 13 m × 18 m × 3.7 m (40 ft × 60 ft × 12 ft) high metal building is a standard design offered by major metal building manufacturers. Each column of the building is mounted on a roller assembly that rolls along standard I-Beam rails. When the building is over the lysimeters, horizontal bi-fold doors at each end close to prevent rain from blowing inside the shelter. Three-phase electric power is supplied to the building through a cable on a take-up reel. Maintenance of the field area is minimized by having the areas between the

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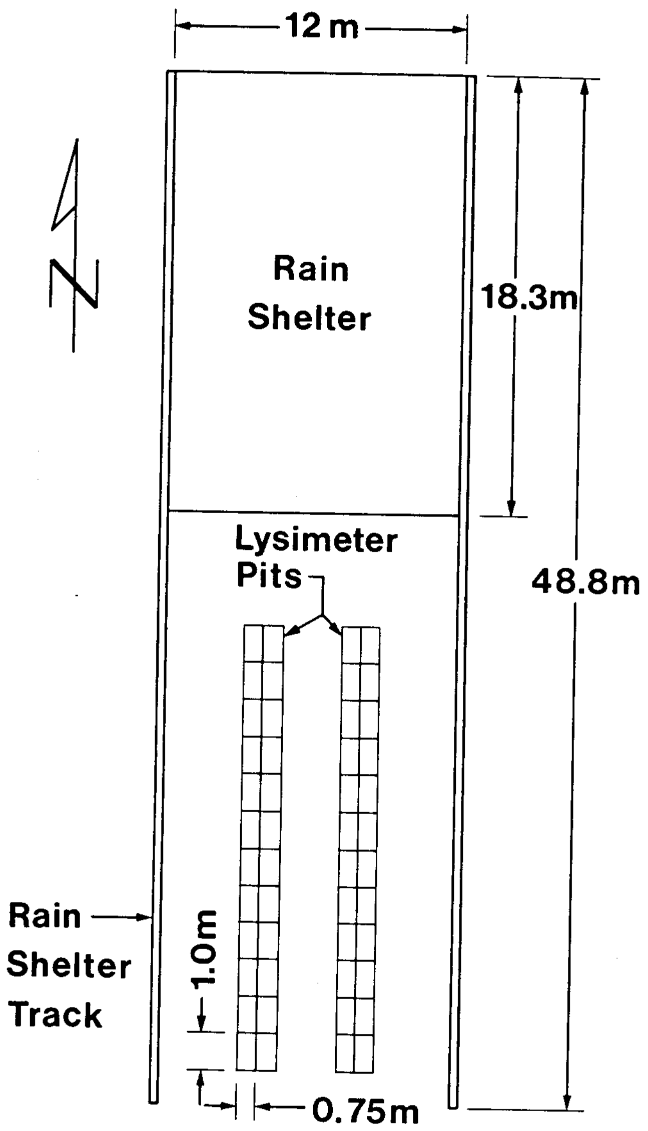

Figure 1–Plan view of evapotranspiration research facility.

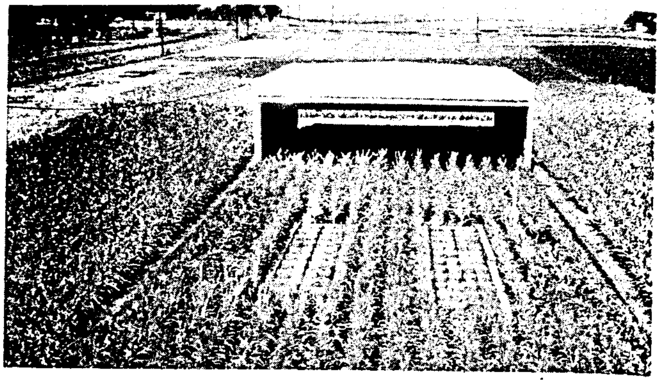

Figure 2–The Bushland evapotranspiration research facility with a mature grain sorghum crop. The grain sorghum on the lysimeters has been harvested for total dry matter measurement.

rail foundations and lysimeter pits sized for field machinery.

Independent drive assemblies on each side of the rain shelter building (Ries and Zachmeier, 1985) move the shelter at a speed of 0.31 m/s (1 ft/s). The speed of each 2.2-kW (3 hp) electric motor is reduced through a belt drive and a shaft-mounted gear reducer. A No. 80, cycloidal, roller-chain sprocket on the driven shaft of the gear reducer meshes with a roller chain stretched along the top of each I-Beam rail. The cycloidal sprocket and roller chain operate as a rack and pinion drive. A dry fluid clutch in each drive assembly provides gradual acceleration of the building and reduced forces on the assembly components. The independent drive mechanisms eliminate any shafts or cable drives across the building, and all drive components are at ground level for easy installation and maintenance.

An Allen Bradley Model SLC 100 programmable controller allows rainfall-initiated automatic control or manual operation of the rain shelter. A Rainbird Model RS-1 automatic rain shutoff mounted on the shelter initiates a control sequence to move the rain shelter from the storage area to the lysimeter area. When the shelter stops over the lysimeters, the controller closes the doors. After a preset interval without rain, the controller automatically opens the doors and moves the shelter back to the storage area. Under manual control, the rain shelter can be moved in either direction, the doors can be opened and closed, and the bridge crane can be operated.

Three system interlocks and a hard-wired crane safety switch protect the rain shelter and crops growing in the lysimeters. The interlocks permit activation of the drive motors only if both doors are in the up position, prevent operation of the doors when the drive motors are energized, and prevent operation of the bridge crane in the automatic mode. The crane safety switch locks out the building drive motors if the bridge crane is located where it can be attached to the lysimeters.

Lysimeter Pits

The two identical lysimeter pits allow a wide range of experimental designs and minimize hand cultivation in the surrounding field (fig. 1). A 0.75-m (30-in.) row spacing is commonly used for row crops in the Southern High Plains, and a 0.25-m (10-in.) row spacing is commonly used for small grains. Crops can also be planted in 1-m (40-in.) spaced rows perpendicular to the lysimeter pits.

The main part of the lysimeter pits are concrete for strength and durability, but the upper 380 mm (15-in.) is steel to minimize the wall thickness at the soil surface (fig. 3). A 305-mm (12-in.) wide flume with a sloping bottom traverses the full length of each pit and channels

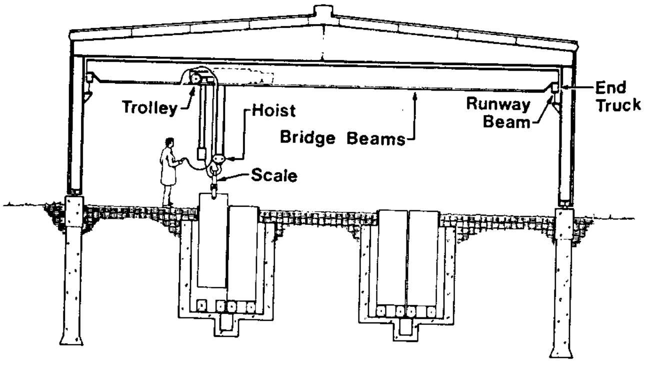

Figure 3–Schematic of double bridge crane, metal building, and lysimeter pits.

drainage water to a sump pump at the north end of each pit. Conduit within the concrete walls protects electric lines to the sump pumps and data lines to the individual lysimeters. Five, 120-V electric outlets along the west side of each lysimeter pit provide electricity for instruments and equipment.

Bridge Crane

A top-running, double-bridge crane is used to lift the lysimeters for weighing and to move them in and out of the pits (fig. 3). This type of crane requires the minimum vertical space for a given load rating. The metal building was designed specifically for the crane, and the crane runway beams sit on chairs that are attached to the building columns. The bridge crane is fully electric-powered with single-station controls at the crane. Capacity of the dual-speed, chain-type hoist is 4.5 Mg (5 tons). Electrical transmission is through a hard-bar system inside the west runway beam.

Load Cell Scale

The mass of the lysimeters is measured with a load cell and digital weight indicator. Evapotranspiration is calculated from mass changes in the lysimeters. The load cell is a Sensotronics Model 60001A10K-5000 rated at 4500 kg (5 tons), and the weight indicator is a Weigh-Tronix Model WI-110 operating from 120 Vac. A Campbell CR-21X is used to record the analog dc voltage signal from the weight indicator. Then, data are recorded on a portable storage module. To increase the accuracy of the measurements, a 3600-kg (4 ton) calibration weight is used to tare the load cell before and after weighing the lysimeters. With this procedure, the mass accuracy or resolution of the weighing system is 0.35 kg (0.77 lb) or 0.47 mm (0.019 in.) of water on the 0.75 m^2 (8.1 ft^2) lysimeter surfaces. This accuracy is suitable for weekly or semi-weekly evapotranspiration measurements throughout the growing season and for some daily measurements with a non-stressed, full canopy crop. Weighing the lysimeters at the same time of the day and in the shaded environment reduces the temperature sensitivity of the load cell.

Irrigation and Drainage Systems

A drip irrigation system is used to irrigate the lysimeters and the field areas around the lysimeter pits. The flow rate of drip emitters over the lysimeters are verified with timed, volumetric measurements at a pressure set with pressure regulator. Irrigation times for individual treatments and for the field area are set with a Rainbird Model MIC-8 irrigation controller. The field area covered by the rain shelter is controlled separately to compensate for the lack of rainfall. Uniform suction drainage has been manually applied to all soil monoliths before planting crops for plant water stress studies.

Monolithic Lysimeters

Amarillo fine sandy loam, Ulysses silt loam, and Pullman clay loam, the three soils selected for the evapotranspiration research facility, are representative of several million hectares (acres) in the Southern High Plains. Monoliths of the three soils were collected near Big Spring, Texas; Garden City, Kansas; and Bushland, Texas, respectively. According to soil taxonomic classification (Soil Conservation Service, 1990), Amarillo soil is a fine-loamy, mixed, thermic aridic Paleustalfs; Ulysses soil is a fine-silty, mixed, mesic aridic Haplustolls; and Pullman soil is a fine, mixed, thermic torrertic Paulestolls. Of the three soils, Ulysses silt loam has the largest soil water holding capacity and least restriction to root development. Amarillo fine sandy loam and Pullman clay loam have calcic horizons starting at 1.0 to 1.25 m (40 in. to 50 in.) depths that often limit rooting development. The Pullman soils have dense clay loam layers in the B horizons that may also restrict plant rooting.

Design and Fabrication

The 0.75-m × 1.0-m × 2.3-m (30-in. × 40-in. × 7.6 ft) deep soil monoliths are designed to provide a full rooting depth of undisturbed soil and normal row spacings. The rectangular surface area represents a small section of either 0.25-, 0.75-, or 1.0-m (10-in., 30-in., 40-in.) spaced crop rows in a large field. Corn, grain sorghum, and wheat, the three major crops in the Southern High Plains, have rooting depths of 2 m (80 in.) or less. Other crops such as sunflower and sugarbeets have rooting depths deeper than 2 m (80 in.), but the equal-depth profiles are expected to provide valid comparisons between the three soils.

The monolith boxes were fabricated from 9.5 mm (3/8 in.), mild steel plate so the un-reinforced, smooth walls would provide adequate strength. To reduce fabrication cost, two opposite corners were bent at 90° angles so that only two corners required welding. Two eyes at the top are used for lifting the monoliths with alloy-chain slip hooks. A 6.4-mm (1/4-in.) pipe coupler for a drainage tube is welded 75 mm (3 in.) from the bottom of one 1-m (4.0-in.) wide wall. The steel boxes are painted inside and outside with lead primer and an industrial enamel finish coat.

Monolith Collection

The soil monoliths were collected with the hydraulic pulldown procedure described by Schneider et al. (1988). Initially, a grid of bell-bottomed piers was installed with space for two monoliths between any four adjacent piers. After the concrete cured, the boxes were individually pressed into the ground with a pulldown frame spanning the four piers and jacking assemblies linking the four corners of the frame to the piers. Figure 4 illustrates the equipment used to press down the monolith boxes in Amarillo fine sandy loam. Hand jacks were modified to operate as remote, single acting hydraulic cylinders, and a 1.5-kW (2 hp) electric-motor-driven pump provided 3.8 L/min (1.0 gal/min) of hydraulic oil at 20.7 MPa (2000 psi). The hydraulic jacks were individually controlled with a valve assembly containing four parallel control valves.

A special cutting edge and dry lubricant were required to prevent compression of the monoliths and to reduce the pulldown force. The monolith boxes were coated on both sides with a chemically-inert, teflon-based dry lubricant before they were pressed into the soil. Initially, the bottom edge of the monolith boxes was beveled 45° from both sides to form a 90° wedge-shaped cutting edge. With the 90° cutting edge, we were not able to press the boxes into the Pullman soil with as much as 480 kN (108,000 lbf) of

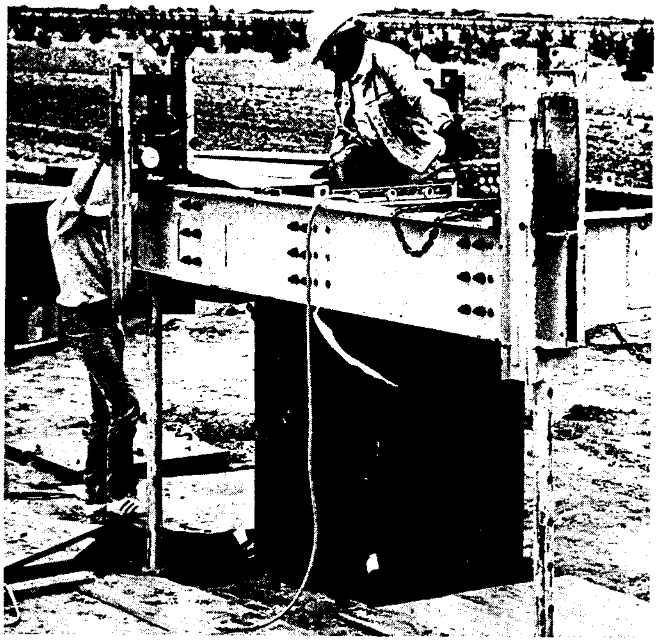

Figure 4–Hydraulic pulldown equipment used to press the monolith boxes into the soil.

force. By beveling the bottom edge 45° to the inside only and adding a 3-mm × 25-mm (1/8-in. × 1-in.) ring around the outside, we were able to press the boxes 2.3 m (7.6 ft) into the Pullman soil with 480 kN (108,000 lbf) of force. Two monoliths collected in this way were compressed 63 and 118 mm (2.5 in. and 4.6 in.) below the soil level outside the box and were discarded. A second 3-mm × 25-mm (1/8-in. × 1-in.) ring was then added to form the cutting edge illustrated in figure 5. The double-ringed cutting edge reduced the maximum pulldown force somewhat, but more importantly it virtually eliminated vertical compression of the monolith. For example, the average compression at the center of 14 Pullman clay loam monoliths was only 5 mm (0.20 in.).

Through experience, we learned that warping of the un-reinforced walls could be controlled with the cutting edge design. With the symmetric, wedge-shaped cutting edge, the walls tended to bend outward. With a single 3-mm × 25-mm (1/8-in. × 1-in.) ring on the outside and a single bevel to the inside, the walls tended to stay straight. Adding a second 3-mm × 25-mm (1/8-in. × 1-in.) ring on the inside with only a single inside bevel caused the walls to bend inward. After our initial experience with the Pullman soil cores, we put a double bevel on the inner ring only (fig. 5) and the walls did not bend in either direction. The beveling of the 9.5-mm (3/8-in.) plate was done with a track-mounted oxy-acetylene torch, and the beveling of the inside and outside rings was done with a hand electric grinder.

The average pulldown forces for the three soils as a function of depth are illustrated in figure 6. The Pullman soil required the largest pulldown forces with an average force reaching 447 kN (100,000 lbf) at the 2.44-m (96-in.) depth. In the 1.0- to 2.0-m (40-in. to 80-in.) depth range, the pulldown forces for the Amarillo and Ulysses soils were 100 to 150 kN (22,500 to 33,700 lbs) less than for the Pullman soil. Both the Pullman and Ulysses soils had plow pans that caused the average pulldown force at the 0.3-m (12-in.) depth to exceed 100 kN (22,500 lbs). Below that depth, pulldown forces increased more slowly for the Ulysses soil and actually decreased for the Pullman soil.

After all monolith boxes at a sampling location were pressed down, a 2.3-m (7.6-ft) long neutron access tube was installed in the center of each monolith with a tractor-mounted hydraulic soil sampler. Then, the surface of each monolith was covered with plastic film, and the empty space above the soil surface was packed with topsoil. The steel boxes were then capped with temporary steel tops so the monoliths could be turned upside down for transportation back to the laboratory.

To remove the monoliths from the ground, a trench was excavated along one wall, the monoliths were tilted into the trench, and then the monoliths were lifted out of the trench. Before a monolith was tilted over, three 0.4-m (16-in.) long, steel wedges were driven horizontally into the soil below the cutting edge. These wedges were chained to the steel box to prevent the monolith from slipping inside the box as it was lifted. The monoliths were transported vertically in an upside down position (fig. 7). This prevented shattering of the monolith during several hours of transport and saved an additional overturning operation to install the drainage system and bottom.

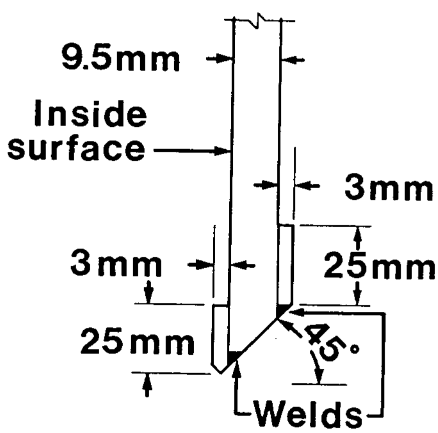

Figure 5–Cutting edge for monolith boxes with inner and outer rings.

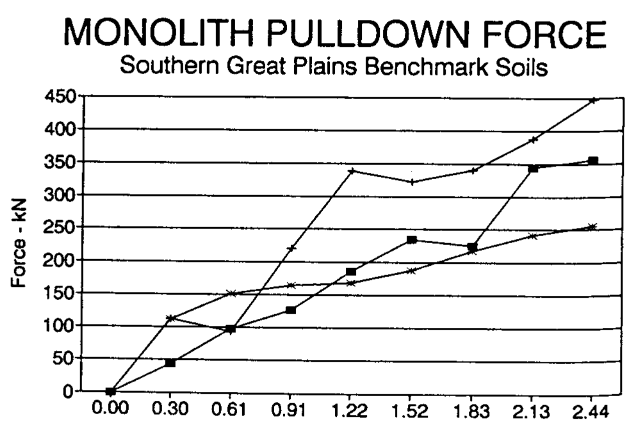

Figure 6–Average monolith pulldown forces as a function of depth for the three soils.

Figure 7–Upside down monolith box ready for loading on truck. The two monoliths on their sides illustrate the soil shear plane.

Table 1. Costs for the rain shelter facility, lysimeter tanks, and monolith collection (costs are in 1989 U.S. dollars)

Item	Contract Cost	Material and Equipment	Labor (Man-Years)
Rain shelter			
Foundations	$ 17,220		
Rails		$ 5,300	0.1
Building with drive mechanisms		20,780	0.4
Electric control system	13,190		
Bridge crane	35,740		
Electric service, power cable and wiring		7,290	0.1
Bi-fold doors		9,670	0.1
Rain Shelter Subtotal	**66,150**	**43,040**	**0.7**
Lysimeter pits	34,200		
Lysimeter tanks (48 tanks)			
Bottomless tanks and bottom plates	43,510		
Painting and welding bottoms	11,440		
Drainage systems		8,370	0.2
Overturning and moving to pits			0.1
Lysimeter Tanks Subtotal	**54,950**	**8,370**	**0.3**
Monolith collection			1.2
Equipment and supplies		5,700	
Anchors		11,990	
Crane service		6,060	
Hauling		5,080	
Miscellaneous		830	
Monolith Collection Subtotal		**29,660**	**1.2**
Load cell scale	3,190		
Drip irrigation system		2,730	0.1
Total	**158,490**	**83,800**	**2.3**

Drainage System Installation

Installing the suction drainage system and welding on permanent bottoms were the final steps before moving the soil monoliths to the lysimeter pits. Approximately 75 mm (3 in.) of soil was removed from the bottom of the monoliths, and a shallow trench was centered parallel to the 0.75-m (30-in.) dimension of the monolith bottom. A sintered, stainless steel drain tube with a bubbling pressure of 12 kPa (120 mb) was installed in the trench and packed in a diatomaceous earth filter approximately 50-mm (2.0 in.) thick. The remaining excavated volume was filled with fine sand having a D50 size of 0.50 mm (0.020 in.). The drain tubes were 38 mm (1.5 in.) diameter × 610 mm (24 in.) long and made of 0.5-µm (0.000020 in.) size particles. After the sand was packed and leveled, 9.5-mm (3/8-in.) thick steel bottom plates were welded to the tanks, and the outside of the tanks were repainted. The monoliths were then turned upright, and moved to the lysimeter pits with a fork lift.

Research Facility Cost

The U.S. Department of Agriculture (USDA) acted as the general contractor for the evapotranspiration research facility, and took responsibility for coordinating the activities of several contractors. In addition to contractor-installed equipment, several items on the rain shelter were installed by USDA personnel. For this reason, Table 1 lists contract costs, material and equipment costs, and labor requirements. The contract, material, and equipment costs are actual costs, and the USDA labor requirements are estimates based on work logs and other records. Fabrication of the monolith collection equipment and collection and preparation of the monoliths were done entirely by USDA personnel. USDA personnel also erected the rain shelter building and installed the drive mechanisms and bi-fold doors. In doing their work, USDA personnel used a machine and welding shop, a 3600-kg (8000 lb) capacity fork lift and flat-bed trucks and pickups that are not listed in the table. In addition to these expenses, USDA engineers provided approximately one man-year of engineering time for the project.

In table 1, expenses are separated so the costs of the main components of the system can be estimated. This allows a potential user to estimate the cost of a similar facility without all of the components. Without the bridge crane, the rain shelter consisting of foundations and rails, building, electric service, and bi-fold doors cost $73,450 and required 0.7 man-years of labor. The main cost of the facility, $168,850 and 1.6 man-years of labor, is for fabricating the monolith containers, collecting the soil monoliths, and additions to the rain shelter facility for handling the lysimeters. The additions were the bridge crane and the lysimeter pits.

Operating Experience

The evapotranspiration research facility has operated satisfactorily during one year of double-cropping with winter wheat and grain sorghum. The drive mechanisms have moved the rain shelter satisfactorily, and the bi-fold doors have operated without problems. With lysimeter weighing and neutron soil water measurements, we have been able to measure crop water use and zones of water depletion within the soil profiles.

Figure 8 illustrates bare soil evaporation rates for the three soils when daily evaporation rates are low. The lysimeters were weighed daily during the first 4 days and

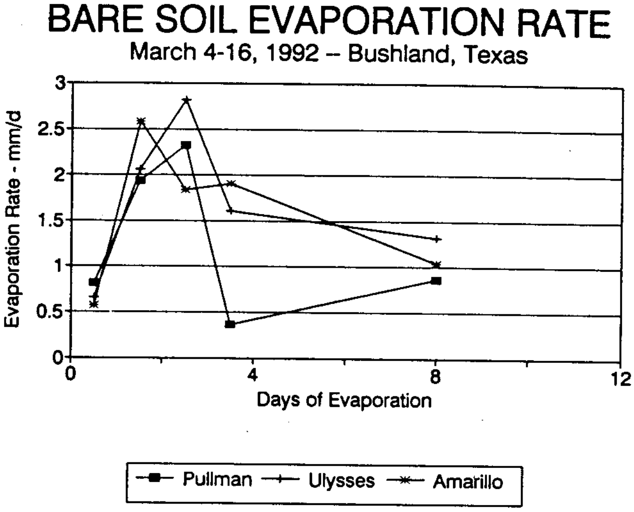

Figure 8–Bare soil evaporation from the three benchmark soils.

one additional time at the end of the 12-day interval. The small evaporation loss during the first day was a result of maximum daily air temperature being about 6° C (10.8° F) lower than during the remainder of the test. The figure illustrates soil evaporation rates less than 1 mm/d (0.04 in./day) and consistent measurements over the 12-day interval.

Some problems that have occurred are inherent in using three different soils and suspending the lysimeters inside the pits during weighing. The three soils have different levels of plant available nutrients that have to be compensated through careful fertilizer applications. Cropping three soils with varying levels of water stress results in uneven plant heights across the lysimeter pits. We have partially offset this effect by blocking experimental treatments that are expected to grow similarly and by irrigating the field areas around the lysimeter to maintain plant growth height similar to that in the lysimeters. The lysimeter pits are larger than the lysimeters so that individual lysimeters can be suspended freely during weighing. This allows cooling of the lysimeters during the winter and snow accumulation in the pits if the rain shelter is not used during snow events.

Operating problems have primarily occurred in using the bridge crane and with the rain sensor. The bridge crane inside the rain shelter substitutes for a gantry crane and allows the lysimeters to be weighed in a sheltered environment. A 3.7-m (12 ft) eave height building was selected for the rain shelter to reduce wind loading on the building and bi-fold doors. With the available head space, lysimeters with crops as tall as 2.4 m (8 ft) can be weighed, but the lysimeters cannot be moved from the pits after crop height exceeds about 0.25 m (10 in.). A commercially-available, over-ride irrigation rain sensor has proven reliable but lacked sensitivity both in initiating movement of the shelter when rain begins and uncovering the lysimeters when rain ends. Modifying the catch pan to concentrate rain water under the two electrodes has improved the sensitivity.

Other problems have been identified that need to be considered in the design of a rain shelter with lysimeters. Runoff from the rain shelter and snow melt sometimes prevent timely tillage operations especially during the winter. Soil compaction around the lysimeter pits has been a serious problem, and we have placed 0.3-m (12-in.) wide expanded steel walkways around the lysimeter pits and confined foot traffic to these walkways. Timely weighing of the lysimeters is important because the weighing is done while the growing crop is covered by the rain shelter. To speed up the weighing operation, we fabricated alloy steel chains and hooks that quickly attach to steel eyes in the lysimeter boxes. We also mounted the load cell instrumentation on a swinging arm attached to the bridge crane so that operators have quick access to the instrumentation while weighing the lysimeters. A trained operator can weigh the 48 lysimeters in about 4 h. High output fluorescent lights provide good lighting for personnel collecting data inside the closed rain shelter. Using field machinery in the area around the lysimeters reduces hand labor, but collection of detailed plant and soil water data from 48 lysimeters has proven to be quite labor intensive.

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